Available online at www.sciencedirect.com
SCIENCE DIRECT
Renewable and Sustainable Energy Reviews
8 (2004) 157–182
ELSEVIER
RENEWABLE & SUSTAINABLE ENERGY REVIEWS
www.elsevier.com/locate/rser

Progress of electricity from biomass, wind and photovoltaics in the European Union

Arnulf Jäger-Waldau *, Heinz Ossenbrink

European Commission, Joint Research Centre, Renewable Energies Unit, Via E. Fermi 1, TP 450, Ispra, VA 21020, Italy

Received 10 October 2003; accepted 13 October 2003

Abstract

The world market for renewable energies is continuously growing. In particular, the wind energy and photovoltaic markets show yearly growth rates between 20 and over 30% in the last few years. Despite the fact that there are still discrepancies between the European Union and the USA how to deal with climate change, renewable energies will play an important role for the implementation of the Kyoto Protocol and the worldwide introduction of tradable green certificates.

Apart from the electricity sector, renewable energy sources for the generation of heat and the use of environmental friendly bio-fuels for the transport sector will become more and more important in the future. This article tries to give an overview about the progress of renewable energies in Europe.

Keywords: Renewable energies; Biomass; Wind energy; Photovoltaic; Energy challenge; Policy options; Technological development; Market development; Kyoto Protocol

Contents

* Corresponding author. Tel.: +39-0332-789119; fax: +39-0332-789268.
E-mail address: arnulf.jaeger-waldau@cec.eu.int (A. Jäger-Waldau).

1364-0321/$ - see front matter
doi:10.1016/j.rser.2003.10.003

1. Energy challenges and options

The increase of the energy consumption of 10% from 1990 to 2000 [1] in the European Union has lead to an increase of energy imports because the commu-

nity's own production is insufficient for the Union's energy requirements. As a result, external dependence for energy is constantly increasing, and is presently about 49%. It is expected that this dependency increases to over 80%, when the European Union enlarges to 25 member states in 2004. In addition environmental concerns nowadays shared by the majority of the public add to the list of weaknesses of fossil fuels and the problems of nuclear energy. These concerns include societal damage caused by the energy supply system, whether such damage is of accidental origin (oil slicks, nuclear accidents, methane leaks) or connected to emissions of pollutants.

The struggle against climate change is a major challenge and a long-term issue for the international community. The commitments made in the Kyoto Protocol [2] can therefore only be a first step. Despite the fact that the union has reached its objectives in 2000 and ratified the Kyoto Protocol in 2002, greenhouse gas emissions are on the rise in the union as in the rest of the world. The return to sustained economic growth on both sides of the Atlantic and in Asia, as well as the need for rural development will increase the energy demand and greenhouse gas emissions further.

What are the energy challenges we are facing?

- Sustainability:
  De-coupling of economic growth from depletion of resources and global warming.
- Security of supply:
  Ensuring long term availability of energy sources.
- Safety of the energy chain:
  Accidents, political stability, import dependence
- Growing demand in developing countries:
  2000 million people have no basic electricity service.
  An electricity distribution grid outside large cities will never be economically viable.

This leads to the question of what are the possible options to face these challenges. The answer to this question leaves us with few options to decrease the energy intensity and, as this is not enough, to increase the union's indigenous energy supply.

- Decrease energy intensity (Mtoe/GNP)

  1. Increase efficiency of energy end-use (domestic, industry, transport)
  2. Increase efficiency of electricity generation

- Increase (indigenous) supply

  1. New and renewable energies
  2. Examine nuclear option

The decrease of energy intensity alone can not solve the problem, as our energy consumption structure, mainly of electricity and for transport, is a consequence of our lifestyle. Furthermore, the public in the industrialised countries is split over the issue of nuclear energy use. Therefore, the future of nuclear energy is uncertain, particularly in Europe. It depends on several factors, including a solution to the problems of managing and stocking nuclear waste, the economic viability of the new generation of power stations, the safety of reactors in eastern Europe, in particular applicant countries, and the global fight against nuclear proliferation.

Renewable energies do not address these safety and security concerns. In addition, there is an abundant supply within the European Union. However, regardless of the type of renewable energy source there are obstacles of a structural nature to their implementation. The current economic and social system is based on centralised conventional sources of energy (coal, oil, natural gas and nuclear energy) and their distribution system. The second main barrier is of a financial nature. Renewables need significant initial investment, as was the case for the other energy sources, such as coal, oil and nuclear energy. We should not forget that most of these investments were either made by public companies or secured by public credit guarantees.

Therefore, the renewable energy market in the European Union cannot be expected to develop regularly without a support policy in the medium term on the part of the public authorities. Support measures stretch from direct subsidies in favour of renewable energy sources or the obligation on the part of electricity producers and utilities to purchase a minimum percentage of electricity produced from renewable sources of energy through to aid to research or financing mechanisms (interest subsidies, guarantee funds, parafiscal tax on other sources of energy).

2. The political frame in the European Union

In December 1997, the European Council and the European Parliament adopted the "White Paper for a Community Strategy and Action Plan" [3]. In this paper the aims were described as follows: "Renewable energy sources may help to reduce dependence on imports and increase security of supply. Positive effects are also anticipated in terms of CO_2 emissions and job creation. Renewable energy sources accounted 1996 for 6% of the union's overall gross internal energy consumption. The union's aim is to double this figure by 2010".

Three years later the Green Paper "Towards a European Strategy for the Security of Energy Supply" [4] was published. The Green Paper highlighted the energy supply dependence of the European Union (50% imported now, with candidate countries 80%) and that if no measures are taken this dependence will rise in the next 20 to 30 years to 70% of the union's energy requirements, as opposed to the current 50%. The enlargement in 2004 will aggravate this trend. Therefore, the European Union's long-term strategy for energy supply and security must be designed to ensure the well-being of its citizen, while respecting environmental concerns and looking towards sustainable development [5].

The target of the White Paper to double the share of renewable energies from 6% in 1995 to 12% in 2010, as well as the Kyoto Protocol commitment to reduce the greenhouse gas emissions by 8% are once more pointed out. The Green Paper also states that at the moment it seems unlikely that nuclear energy will see renewed growth. This is due to the liberalisation of the energy markets and its competitive position compared with other energy sources (e.g. natural gas), public acceptance and a possible solution to the problem of nuclear waste. At the present political situation (the decision by certain member states to relinquish this sector), it is likely that the contribution of nuclear energy will change little from now until 2020.

The increasing demand for energy of the transport sector (+50% until 2010) and its 98% dependence on oil creates a further demand for renewable energies, e.g. bio-fuels). This is of particular importance as the European Union is already 76% (EU15) dependent on oil imports and it is likely to rise to 94% (EU30) in 2010 if business as usual is pursued.

Last, but not least, the role of the European Union as a player in the world energy market is an argument to promote renewable energies. As the EU relies on imported energy, the dependence on supply and demand conditions in the international market have to be taken into account. Therefore, the forecasted rise by some 65% over 20 years, from 9.3 billion toe in 2000 to 15.4 billion toe in 2020, due to the world's population growth and the growing demand of developing countries, will have a substantial impact on international fossil fuel prices. International efforts to promote renewable energy and energy efficiency are necessary to reduce this trend.

3. Instruments of the European Commission

The main instruments of the European Commission to implement the Kyoto Protocol are the different Directives to promote renewable energies and measures to increase the energy efficiency in the union. In the following the main directives are listed and shortly described.

3.1. Directive on the promotion of electricity produced from renewable energy sources in the internal electricity market

3.1.1. Main aspects of this directive [6]

Indicative targets were set for the member states (Figs. 1 and 2), but the member states have the freedom until 2005 to choose the kind of measures and incentives they want to use to reach the targets. The member states are obliged to report about the progress of implementation and the success of the chosen methods every 2 years. On 27 October 2005 the Commission has to present a report on experience gained with the application and coexistence of the different mechanisms. If necessary, the report should be accompanied by a proposal for a community framework with regard to support schemes for electricity produced from renewable energy sources to ensure that the targets for 2010 are met.

The directive also regulates the grid access and obliges the member states to ensure a nondiscriminating treatment of electricity generated by renewable energies.

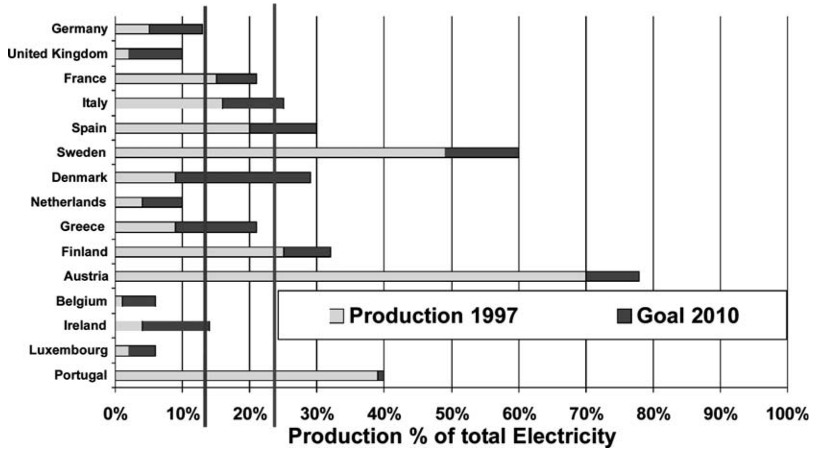


Fig. 1. Indicative renewable energy targets set in the directive for the different member states. The blue line is 1995 (12%) and the green line 2010 (22%).

3.2. Directive on the energy performance of buildings

3.2.1. Main aspects of this directive [7]

The objective of this directive is to promote the improvement of the energy performance of buildings within the community, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness.

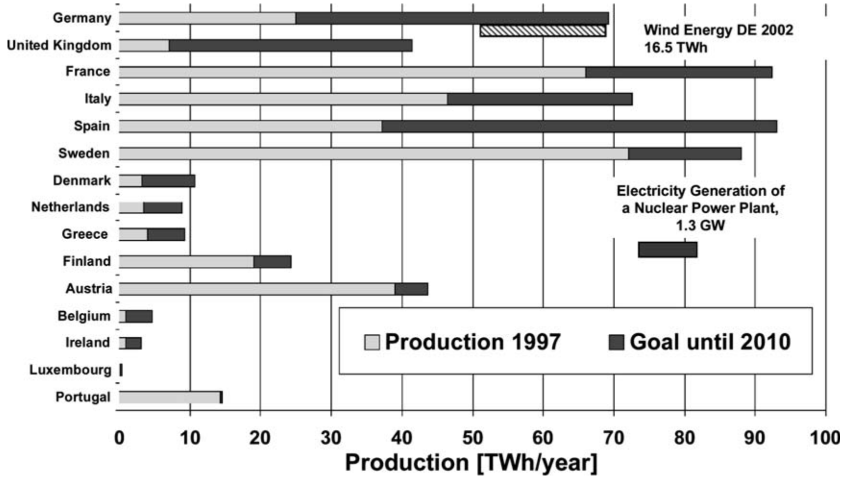


Fig. 2. Indicative targets for electricity from renewable energies in TWh. The blue bar shows for comparison the electricity generated by a nuclear power plant with 1.3 GW capacity under the assumption of 7000 h annual operation. This corresponds to a 80% availability. The hatched bar shows the actual produced electricity by wind in Germany in 2002. Wind turbines have on average 2000 h annual operation.

The following requirements are laid down by the directive:

- The general framework for a methodology of calculation of the integrated energy performance of buildings;
- Application of minimum requirements on the energy performance of new buildings;
- Application of minimum requirements on the energy performance of large existing buildings that are subject to major renovation;
- Energy certification of buildings;
- Regular inspection of boilers and of air-conditioning systems in buildings and in addition an assessment of the heating installation in which the boilers are more than 15 years old.

Renewable energies are mentioned in particular with respect to new buildings over 1000 m^2 floor space. In addition, they play an important part in the general framework for the calculation of the energy performance of buildings.

3.3. Directive on the promotion of the use of biofuels or other renewable fuels for transport

3.3.1. Main aspects of this directive [8]

Member states should ensure that a minimum proportion of biofuels and other renewable fuels is placed on their markets, and to that effect, shall set national indicative targets. The reference values for these targets shall be 2%, calculated on the basis of energy content, of all petrol and diesel for transport purposes placed on their markets by 31 December 2005 and 5.75%, by 31 December 2010.

Starting in 2004, the member states have to report to the commission before 1 July about:

- Measures taken to promote the use of biofuels or other renewable fuels to replace diesel or petrol for transport purposes.
- National resources allocated to the production of biomass for energy uses other than transport.
- Total sales of transport fuel and the share of biofuels, pure or blended, and other renewable fuels placed on the market for the preceding year. Where appropriate, member states shall report on any exceptional conditions in the supply of crude oil or oil products that have affected the marketing of biofuels and other renewable fuels.

In their first report in 2004 the member states shall indicate the level of their national indicative targets for the first phase and in 2006 the targets for the second phase. The commission has to present a first evaluation report for the European Parliament by 31 December 2006 and every 2 years thereafter. The report should describe the progress made in the use of biofuels and other renewable fuels in the member states. On the basis of this report, the commission shall submit, where

appropriate, proposals to the European Parliament and to the council on the adaptation of the system of targets. If the report concludes that the indicative targets are not likely to be achieved, these proposals shall address national targets, including possible mandatory targets, in the appropriate form.

3.4. Proposed directives

3.4.1. Proposal for a directive on the promotion of co-generation based on a useful heat demand in the internal energy market COM (2002) 415 and COM (2003) 416

3.4.1.1 Main aspects of this proposal. This directive is modelled to some extent on the Renewables Electricity Directive. To ensure that incentives are provided only to efficient CHP systems the directive has to provide a definition of CHP Quality and CHP Certification. Member states will be required to set national targets in accordance with the EU-wide CHP target from 1997. Issues concerning the grid access, cost of connection as well as streamlining administrative procedures have to be addressed.

The CHP directive will cover technologies ranging from small-scale CHP in the residential and tertiary sectors to industrial CHP and CHP with district heating, with special provisions to promote small-scale CHP and renewables CHP.

3.4.2. Proposal for a directive on establishing a framework for the setting of eco-design requirements for energy-using products and amending council directive 92/42/EEC; COM (2003) 453

3.4.2.1 Main aspects of this proposal. The directive will contribute to the security of energy supply and enhance the competitiveness of the EU economy. Improve the overall environmental performance of these products and thereby protect the environment. Ensure free movement energy-using products within the EU and preserve the interests of both industry and consumers.

3.4.3. Proposal for a directive on energy demand management (COM (2001) 580)

3.4.3.1 Main aspects of this proposal. Requirement for the member states to set targets to promote and support energy demand management with efficient technology new services and programmes. A special focus should be on smaller energy consumers such as households and small- and medium-size enterprises. Adapted to each member states' liberalised market, a supportive framework for implementation, financing and monitoring of energy efficiency improvement targets has to be included. In addition to the publicly financed energy efficiency activities the directive will also set a certain minimum level of investment for energy efficiency and demand management, mainly through business-driven activities.

The development of a market for energy-efficient technology and demand management services will be a requirement for member states and they will have to report, on an annual basis, to the European Commission on the amount of investment, the energy saved, and, when possible, the cost-effectiveness of the investments. To do so member states will have to use standardised evaluation methods for monitoring the energy savings and cost-effectiveness of the activities implemented as well as for their reporting to the European Commission.

3.4.4. *Proposal for a framework directive for minimum efficiency requirements for end-use equipment (COM (2001) 580)*

3.4.4.1 Main aspects of this proposal. Establishment of ambitious and cost-effective energy efficiency targets, which then will be implemented through implementing directives. A regulatory committee consisting of member state experts which will be given a mandate in the framework directive, will carry out the work. The setting of minimum efficiency requirements will play an important complementary role to the labelling of products (Council Directive 92/75/EEC) and to voluntary commitments by the industry.

4. Technologies

In order to achieve the White Paper target of 12% renewable energies and 23% electricity from renewable energies for the European Union (EU15) by 2010 indicative targets for different renewable energy technologies were set. The main challenges are within the following technologies: biomass, wind and photovoltaic where the planed increase of electricity production is 10, 20 and 100 times, respectively (Table 1).

The following paragraphs will give an overview about the different renewable energy technologies, their options and their status of implementation.

The conventional energy conversion chain to convert fossil or nuclear fuels into electricity is depicted in Fig. 3. This is done for comparing it with the different renewable energy technologies.

Combustion is the first step in the total conversion chain from fossil fuels to electricity. Chemical energy stored in the fuel is converted into thermal energy. In the case of nuclear fuels a controlled nuclear reaction converts the chemical energy into thermal energy. The thermal energy is then transformed via a steam generator into mechanical energy used in a turbine. The mechanical energy drives a gener-

Table 1
Estimated Contribution for different energy sources in 2010 as set out in the White Paper

Type of energy	Installed capacity		Electricity produced (TWh/a)		Increase of TWh
	1995	2010	1995	2010	
Wind	3 GWe	40 GWe	4	80	×20
Hydro (large)	83 GWe	91 GWe	270	300	×1.11
Hydro (small)	10 GWe	14 GWe	37	55	×1.35
Photovoltaic	0.03 GWe	3 GWe	0.03	3	×100
Biomass	45 Mtoe	135 Mtoe	23	230	×10
Geothermal: el.	0.5 GWe	1 GWe	4	7	×1.75
TOTAL			337	675	×2
Total electricity consumption			2366	2870	
Share of RE			14%	23.5%	

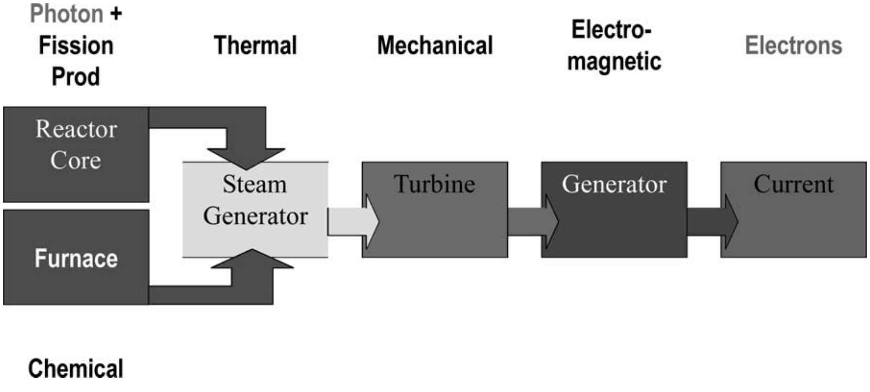


Fig. 3. Conventional energy conversion chain.

ator, which via a electromagnetic energy conversion generates electrons and the electric current.

The First Law of Thermodynamics tells us that the energy is conserved in all its transformations. So, the ratio of energy output to energy input is always unity, or 100%. From this it is obvious that the efficiency of conversion devices is important, i.e. to obtain the best change into every form with the least amount of undesirable "loss" in the form of energy which cannot be used, e.g. heat or waste fuel. This shows that due to the different energy transformation steps in this conversion chain, a considerable amount of the primary energy is converted into energy forms, which cannot be utilised and therefore are considered as losses.

4.1. Biomass

As already pointed out in the Green Paper, the world's markets rely heavily on the fossil fuels coal, petroleum crude oil, and natural gas as sources of energy, fuels, and chemicals. The fact that the demand for these raw materials is increasing constantly and millions of years are required to form fossil fuels in the earth, their reserves are finite and subject to depletion as they are consumed. Biomass is the only other naturally available, energy-containing carbon resource known that is large enough to be used as a substitute for fossil fuels.

What is biomass? All non-fossil organic materials that have an intrinsic chemical energy content are biomass. This include all water- and land-based vegetation and trees (virgin biomass) and all waste biomass such as municipal solid waste (MSW), municipal biosolids (sewage) and animal wastes (manures), forestry and agricultural residues, and certain types of industrial wastes. Biomass is renewable in the sense that only a short period of time is needed to replace what is used as an energy resource.

Via photosynthesis solar energy is harvested and stored as fixed carbon in biomass. Photosynthesis converts carbon dioxide (CO_2) into organic compounds. This

initial step of the production of virgin biomass can be described by the equation:

$$CO_2 + H_2O + \text{light} + \text{chlorophyll} = (CH_2O) + O_2.$$

The primary organic product is carbohydrate (CH_2O). Each gram mole of fixed carbon represents about 470 kJ. In general the capture efficiency of the incident sunlight in biomass is in the 1% range or less. Nevertheless the global energy potential of virgin biomass is very large even if we take into account that there is a competition with food production. There are estimates that the world's existing biomass carbon, i.e. the renewable, above ground biomass that could be harvested and used as an energy resource, is about 100 times the world's total annual energy consumption.

The different sources of biomass can be used for different applications by different routes. Fig. 4 gives an overview of these possibilities.

On average, virgin biomass is harvested for food, feed, fiber and construction material or it is left in the growth area where natural decomposition takes place. Virgin biomass and any waste biomass, which results from the processing or consumption of virgin biomass, can be transformed either into electricity and heat or into fuels and chemicals. There are a variety of technologies to convert biomass by combustion, gasification, anaerobic digestion or landfill gases via thermal processes into electricity and heat, or to use fermentation or esterification methods to obtain liquid fuels (Table 2).

4.1.1. Combustion

Example: wood-fuelled power plants in which wood, wood wastes and agricultural wastes are combusted for the production of steam, which is passed through a steam turbine to generate electric power, heat or both (CHP).

$$C_6H_{10}O_5 + 6O_2 \rightarrow 6CO_2 + 5H_2O + 17.5\ \text{MJ/kg}$$

Status	Burners up to 50 MW, FBR Systems approximately 10 MW;
Development	500 kW ceramic gas-turbines for biomass-powder.

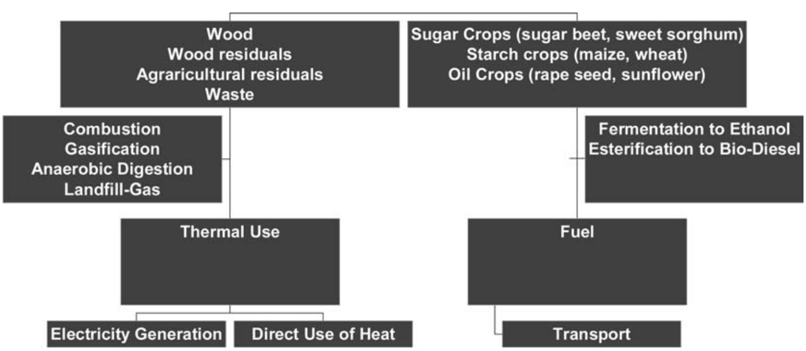


Fig. 4. Overview about the different possibilities to use biomass.

Table 2
Overview about different biomass technologies and their application [9]

Biomass technology	Energy product	Application
Combustion (domestic scale)	Heat (cooking, space heating)	Widely applied; improved tech. Available
Combustion (industrial scale)	Process heat, steam, electricity	Widely applied; potential for improvement
Gasification/power production	Electricity and heat (CHP)	Demonstration phase
Gasification/fuel production	Hydrocarbons, methanol, H_2	Development phase
Hydrolysis and fermentation	Ethanol	Commercially applied for sugar/starch crops; production from wood under development
Pyrolysis/production of liquid fuels	Bio-oils	Pilot phase; some technical barriers
Pyrolysis/production of solid fuels	Charcoal	Widely applied; wide range of efficiencies
Extraction	Biodiesel	Applied
Digestion	Biogas	Commercially applicable

4.1.2. *Gasification*

Example: gasification of rice hulls by partial oxidation to yield a low-calorific-value fuel gas, which drives a gas turbine to generate electric power.

$$C_6H_{10}O_5 + 0.5O_2 \rightarrow 6CO + 5H_2 + 1.85\ \mathrm{MJ/kg}$$

Status	Small, external heated systems, Tar problems;
Development	Heat-recovery, larger gas-turbines with FBR.

4.1.3. *Anaerobic digestion*

Example: anaerobic digestion of biosolids to yield a relatively high-methane-content fuel gas (biogas) of medium-calorific-value.

$$C_6H_{10}O_5 + H_2O \rightarrow 3CH_4 + 3CO_2$$

Status	Developed technology for waste treatment;
Development	Optimised growth of bacteria, combined systems for agricultural residuals.

4.1.4. *Pyrolysis*

Example: Pyrolysis or thermal decomposition of MSW yields to liquid fuel oils and chemicals.

Decomposition at 300–700 °C under the absence of oxygen

Status	Basically charcoal production, small "flash" pyrolysis systems for oil production;
Development	Combination with gasification, bio-oil upgrading hydropyrolysis for hydrogen storage.

4.1.5. Esterification

Example: rapes, from which glycerines and rapsmethylester can be extracted and converted to high-cetane biodiesel fuels.

3 t rapes $\rightarrow$ 1.9 t feed stuff $+$ 1 t rape seed
1 t rape oil $\rightarrow$ 0.11 t glycerines $+$ 1 t RME (rapemethylester)

Status	Well developed, commercially exploited in FR, DE, IT. Can be mixed up to 50% with normal diesel fuel;
Development	Reduction of odour problems, engine optimisation.

4.1.6. Bioethanol

Example: hydrofining of tall oils from wood pulping to obtain high-cetane diesel fuels. Another example for microbial conversion is the alcoholic fermentation of corn to obtain fuel ethanol for use as an oxygenate and an octane-enhancing additive in motor gasolines.

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

This is of interest with respect to the Directive of the European Commission for mixing 6–8% bioethanol with diesel.

Fig. 5 shows that without major changes biomass is suitable to substitute fossil fuels in the energy conversion chain. As listed above, a multitude of biomass conversion technologies exist and can be employed to obtain electricity, heat, fuels, and chemicals.

The technologies are sufficiently variable so that the synthetic fuels produced are either identical to those obtained from fossil feedstock, or suitable as fossil fuel substitutes. In addition it should be emphasised that all fuels and chemicals currently manufactured from fossil fuels can be manufactured from biomass feedstock. The key to the large-scale production of electricity, heat, fuels and commodity chemicals from biomass is to grow suitable virgin biomass species at costs that permit the biomass to be grown at a profit as an energy crop.

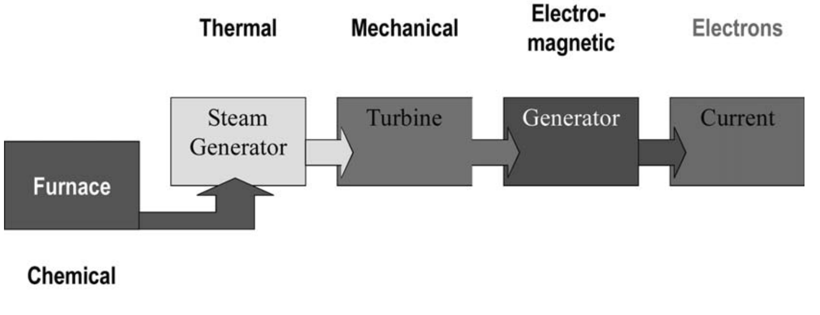


Fig. 5. Biomass energy conversion chain.

In order to achieve this goal the following strategy is needed:

- Secure existing bioenergies in agricultural areas
  Sustainable forestry and agriculture.
- Establish new technologies in existing markets
  Introduction of bioenergy crops (10% of European agricultural area can replace 10% of diesel fuel).
- Exploitation of innovation and research results
  Hydrogen from biomass.

4.2. Wind

A significant and powerful renewable energy resource is wind energy. The wind energy resources are plentiful, globally speaking they are more or less equally distributed and offer the option of both, decentralised and centralised (mainly offshore) power generation. Fig. 6 shows the European wind resources.

At the end of 2002 approximately 32,000 MW of wind power were installed worldwide [10]. These installations provide enough electricity to supply about 16 million European households or 40 million people. About 75% of these installations are in Europe and the five biggest installer countries, Germany, Spain, USA, Denmark and India make up for more than 80%. This uneven contribution leads to hope and concern at the same time. What happens if the leading installers slow down? What happens if the other countries catch up?

The promising outlook is that almost 50 countries worldwide are already installing wind power and contribute to the global growth. In the meantime the industry has become a significant employer with a workforce of approximately 90 to 100,000 people. In addition to the traditional wind market a new segment is about to emerge: offshore wind farms. In the seas around northern Europe wind farms with more than 20,000 MW are already proposed. Similar considerations are also under way in the shelf areas along the American Atlantic cost.

If one looks a the situation in Europe (Fig. 7), it becomes obvious that the increase in installations are not directly correlated with the natural resources, but with the policy support for renewable energies.

The pathways to support renewable energies and here in particular wind energy are somewhat different in Germany, Spain and Denmark, but the most important issue is the creation of investors' confidence to reclaim their investment costs.

The big breakthrough for the German market came in 1991, when the Stromeinspeisungsgesetz—Electricity Feed-in Law (EFL)—was passed by Parliament. This legislation guaranteed to all renewable energy producers up to 90% of the domestic sale price of electricity for every kWh they generated. The law which has proved to be administratively simple and effective in practice was based on the argument that clean energy sources need encouragement both to establish a market and to compete with historically subsidised fuels like coal and nuclear. In 2000 a new renewable energy law was passed which recognised the different energy generation cost for different renewable energy sources and set different guaranteed feed-in tariffs

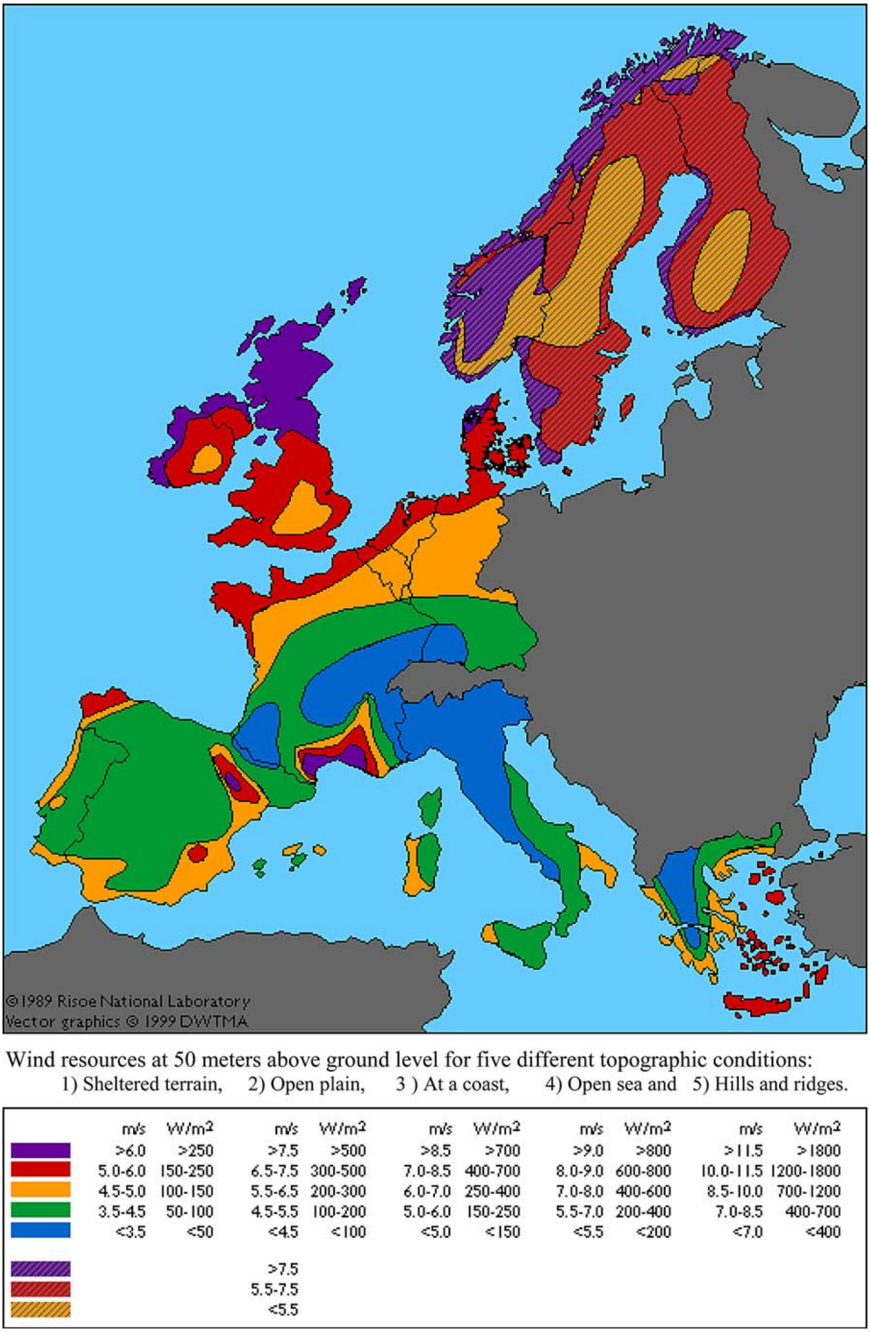


Fig. 6. European wind resource map © Risø National Laboratory (Vector graphics map by courtesy of the Danish Wind Turbine Manufacturers Association).

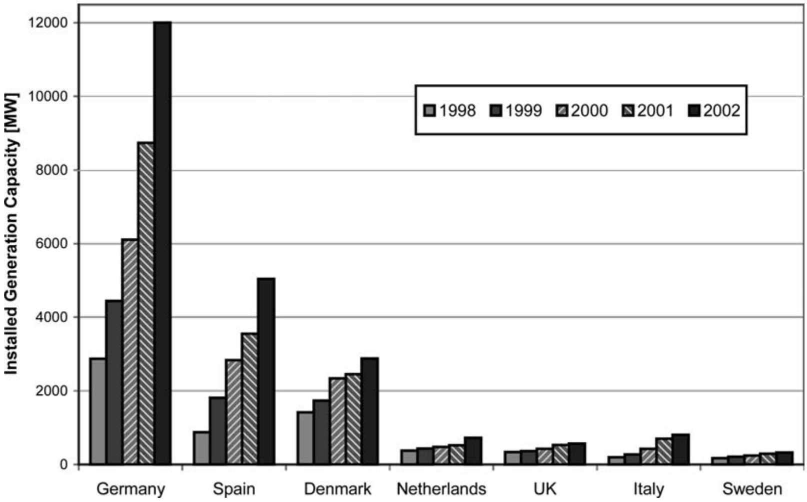


Fig. 7. Wind energy growth in EU top 7.

for the different renewable energies for a certain number of years. In addition, the increasing competitiveness of wind let to an introduction of a decreasing feed-in price after 5 years of a turbine's operation.

A similar system of feed-in tariffs was introduced in Spain, when in 1994 [11] all RES-E electricity producers were entitled to sell their output power to the grid. The amount paid to the RES-E producers must be between 80 and 90% of the average electricity price estimated each year by the government. At the end of 1998 the Royal Decree 2818/1998 which came into force 1 January 1999 strengthened the implementation of renewable energies. It confirmed the targets set by the European Union for Spain of 12% total energy and 29.4% electricity from renewable energy sources in 2010. The royal decree has lead the RES-E producers to opt for a fixed price or a "market price + premium". The main difference to the German system is that the price is not fixed for a certain number of years but is decided from a year to year basis. For 2003, the government agreed price is 6.2 €ct./kWh, making wind a quite attractive investment.

Denmark chose the pathways of national energy plans were already the first Danish energy plan in 1981 set a goal of 10% of the electricity consumption should be come from wind energy in 2000. This target was already met in 1997. The new "Energy 21" plan set massive CO_2 reduction targets (20% cut in the 1988 emission level by 2005 and a 50% cut by 2030). If this should be achieved with renewable energies, more than a third of all energy has to be renewable and most of it will probably be wind. This policy also led to the creation of a new wind industry, which provides more than 20,000 jobs in Denmark—more than the whole energy sector—and over 4,000 jobs abroad.

Besides the political framing conditions another important driving force is technological development. As shown in Fig. 8 the energy convention chain for wind

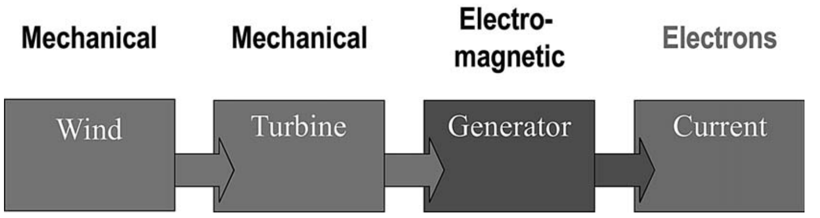


Fig. 8. Wind energy conversion chain.

energy already starts at the mechanical step. The most common configuration is the horizontal axis three bladed turbine with its rotor positioned upwind—on the windy side of the tower, even if a number of other variations are continued to be explored. The main improvements are being made in the ability of the machines to capture as much energy as possible from the wind at the lowest cost. The options are more powerful rotors, larger blades, improved power electronics, better use of composite materials and taller towers.

The most dramatic improvement has been the increase in the size and the performance of the wind turbines which had an direct impact on the electricity cost generated by wind turbines (Fig. 9). In 1982 the average machine had 25 kW, this rose to 200 kW (35 m rotor size) in 1992 and has reached a commercial size range in 2002 between 600 kW and 2500 kW (80 m rotor size on 70 to 100 m high towers). In 2002 the average capacity of wind turbines in Germany was 1390 kW. Bigger machines with 3000 to 5000 kW, especially for offshore applications, are currently under development. The largest prototype, a 4500 kW wind turbine by Enercon was installed in 2003 on a 112 m high tower.

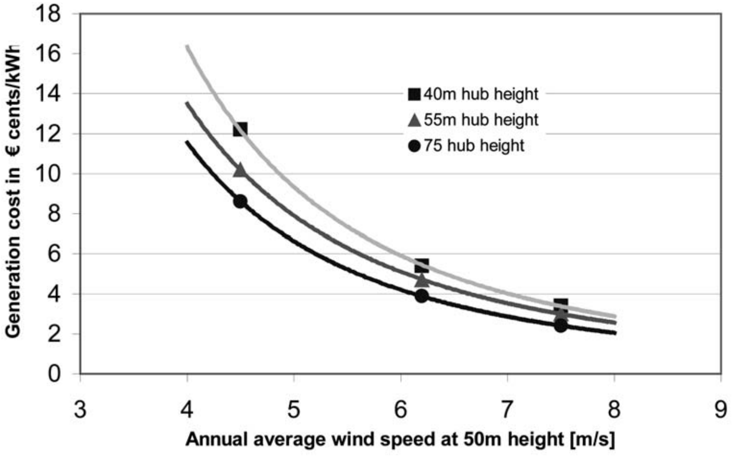


Fig. 9. Generation cost compared to hub height of wind turbine.

Additional developments were aimed to optimise the rotors for low noise emission and to use pitch control. Asynchronous generators, often without reduction gear have gained an approximate market share of 30%.

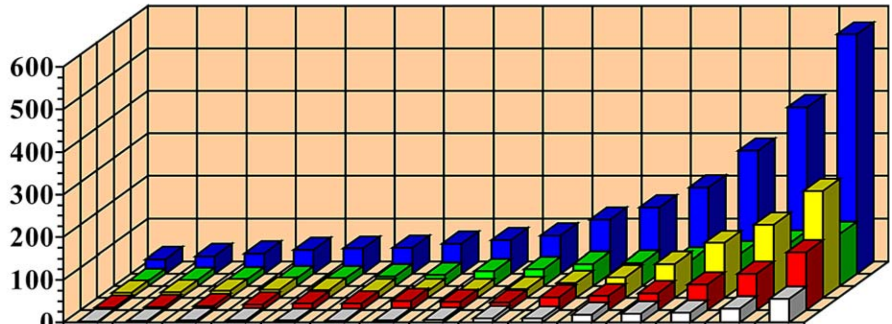
Prices for wind turbines and related to this the price for the kWh electricity generated by wind energy have decreased significantly of the last couple of years. Under favourable conditions, the state of the art wind turbine in 2002 had an investment of €823 per installed kW and electricity costs of 3.88 €ct./kWh [10]. The design lifetime of wind turbines is now in the range of 20 to 25 years. Operation and maintenance costs are typically in the order of 3 to 5% per year of the initial investment costs. The "Wind Force 12" study predicts a further decrease of costs due to an improvement both in the average size of turbines and in their capacity factor. By 2010 the study expects costs of 2.93 €ct./kWh, assuming a cost per installed kilowatt of €623/kW and 2.34 €ct./kWh with an installation cost of €497/kW by 2020. The latter is a substantial reduction of 40% compared with 2002.

The following development trends can currently be seen to achieve the above mentioned price reductions.

- Weight-reduction, advanced materials;
- Better damping of oscillations (blade and tower);
- Flexible components (blades, hubs);
- Reduction of component number;
- Passive alignment, "downwind" rotor;
- More precise forecasting (EnviSat experiment);
- Control of large wind farms;
- Off-shore systems, siting.

4.3. Photovoltaic

In 2002, the photovoltaic industry delivered worldwide some 560 MWp [12] of photovoltaic generators (Fig. 10) and has become a €3.5 billion business. In the past 5 years, the yearly growth rate was an average of 30%, making further increase of production facilities an attractive investment for industry. As about 85% of the current production involves crystalline silicon technology, scale-up of production capacity for this technology will be required in the same proportion. This is a well-established market, which achieves sufficient efficiency for at least 20 years of lifetime and constitutes a low-risk investment with high expectations for return on investments. Should growth in this technology continue as in the past years, the supply of cost-effective silicon feedstock might limit the achievable cost reduction, especially if feedstock costs cannot be kept below about 0.50 €/Wp. In the last years this problem was often mentioned as the bottleneck for the further growth of the silicon wafer based PV industry. But in March 2003 Solar Grade Silicon LLC announced the full production of polycrystalline silicone for PV at the Moses Lake facility with an initial capacity of 2000 metric tons [12]. This indicates



	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Rest of World	3	4	4,7	5	4,6	4,4	5,6	6,35	9,75	9,4	18,7	20,5	23,42	32,6	55,5
Europe	6,7	7,9	10,2	13,4	16,4	16,55	21,7	20,1	18,8	30,4	33,5	40	60,66	86,38	135,1
Japan	12,8	14,2	16,8	19,9	18,8	16,7	16,5	16,4	21,2	35	49	80	128,6	171,2	251,1
United States	11,1	14,1	14,8	17,1	18,1	22,44	25,64	34,75	38,85	51	53,7	60,8	74,97	100	120,6
Total	33,6	40,2	46,5	55,4	57,9	60,09	69,44	77,6	88,6	125,8	154,9	201,3	287,7	390,2	561,8

Fig. 10. World PV cell/module production from 1988 to 2002 (data from PV News [12]).

that the silicon producers have recognised PV as a fully-fledged industry, which provides a stable business for the silicon industry, which traditionally depended strongly on the demand cycles of the microelectronic industry. Therefore, it can be expected that silicon feedstock will be available for the further growth of the PV industry.

Similar to learning curves in other technology areas, a second generation of devices will steadily increase its market share, until the previous, first technology will be replaced. This second generation technology, after years of research and technology—and also lawsuits—is readily available and in the process of transition from pilot to industrial production. Equally competitive technologies are amorphous silicon, CdTe and $Cu(In,Ga)(S,Se)_2$. The growth of these second generation technologies will be accelerated by the positive development of the PV market as a whole and there are many indications that the required scale-up to manufacturing units of 50 MWp yearly capacity will soon join 1st generation silicon devices in satisfying demand. However, the growth of thin film production capacity within this decade must be at least 40% to achieve a market share of 50% in the photovoltaic production of 2010, assuming that total PV growth continues at a constant 27% per year. By then, Silicon technology would deliver about 1500 MWp per year, requiring probably 12,000 metric tons of Si-feedstock, about half of today's entire silicon world production, and one can speculate that thin-film technology will continue to grow even faster. Further cost reduction will depend not only on the scale-up benefits, but also on the cost of the encapsulation system, as efficiency will remain limited below 15%, stimulating strong demand for very low area-proportional costs.

However, thin film PV technologies still have to overcome some major hurdles to realise this vision. The following issues are common ones for all thin film solar cells:

- Currently thin film solar cells have less than 10% market share.
- Large plants with high yield and throughput required for significant cost reduction.
- Efficiency of thin film modules in production are not yet above 10%.
- Most of the thin film modules still have to solve the problem of long-term stability (20 to 25 years of lifetime), which is very much related with encapsulation issues.

But:

- Excellent for building-integration; more flexible in appearance, size and design.
- Enormous potential for growth and investment, in particular for pilot lines.

If photovoltaics are to contribute significantly to the energy supply of the future, new developments for solar cells with higher efficiencies than the current average efficiency for modules made from wafer silicon solar cells (10 to 15%) and somewhat lower for thin film modules (6 to 12%) are needed. There is likely to be an evolution of the current silicon wafer technology to thinner wafers, ribbon or multicrystalline material and more advanced cell technologies. However, an important message from Prof. Martin Green from the University of New South Wales is, that future photovoltaics has to be thin film, whether conventional, concentrator-type or novel ideas, in order to meet the price targets shown in Fig. 11.

In principle the photovoltaic energy conversion chain is very simple and appealing (Fig. 12). However, in reality it is quite challenging to design and manufacture a cheap solar cell. The reasons for this are mainly the area costs and the different

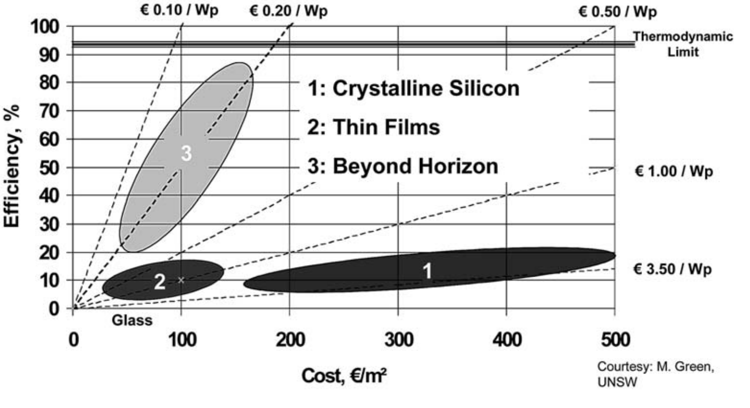


Fig. 11. First, second and future generation solar cells or "which price for what efficiency?"

Fig. 12. Photovoltaic energy conversion chain.

loss mechanisms in the current solar cell concepts. In Fig. 13 the different loss mechanisms are shown for the example of a laboratory prototype and a commercial crystalline silicon solar cell.

To reach the goal of higher efficiencies, several options are currently discussed such as:

4.3.1. "Multiple threshold" or multi-junction devices

Two main losses in the single junction solar cell are due to the fact that all energy of photons smaller than the bandgap ($E_{ph} < E_g$) cannot be converted into electricity and that the fraction of the energy above the bandgap of photons with $E_{ph} > E_g$ is lost as well. If the solar spectrum is split into narrow wavelength bands and converted in separate solar cells with appropriate energy bandgaps, the energy conversion efficiency can be increased. The theoretical efficiency limit for an infinite number of stacked solar cells for direct sunlight is 87%. However, it is clear that this limit can not be reached for a real stack. Nevertheless, a stack with three or four solar cells can increase the efficiency considerably and reach efficiencies well above 35%.

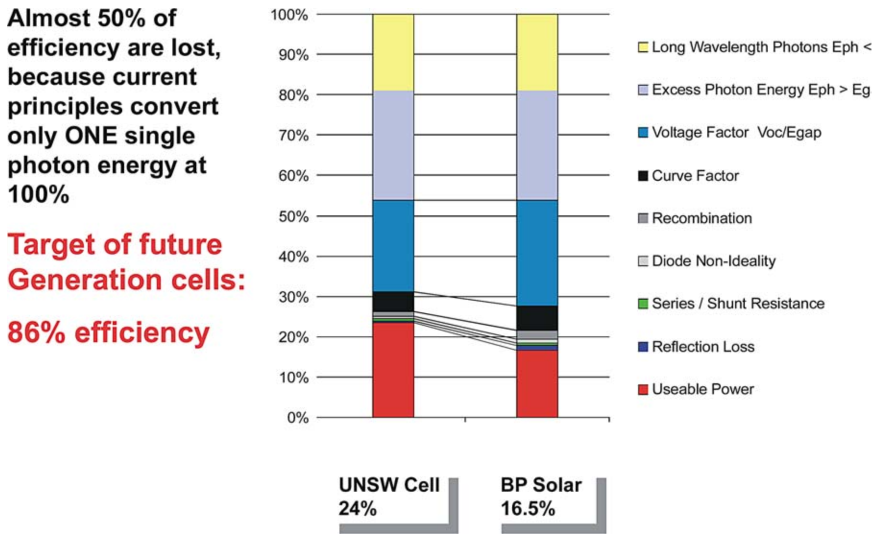


Fig. 13. Loss mechanisms in prototype (UNSW) and commercial (BP-Solar) crystalline silicon solar.

Such a stack is engineered in a way that the solar cell with the highest bandgap is on top and those with the lowest at the bottom. The uppermost cell will then absorb the high energy photons it is able to convert, passing photons of energy below its bandgap through to the underlying cell, where the process continues.

These multi-junction devices are in general used in conjunction with a concentrator technology, i.e. the sunlight is concentrated onto the solar cell, in order to save on the solar cell material.

4.3.2. Quantum mutiplication

This can be realised with up- or down-conversion. In the case of up-conversion, two sub-band-gap photons, which would not be absorbed by the solar cell, are transformed to one larger energy photon, which is absorbed by the solar cell. This process can also be reversed to down-conversion, where one large energy photon, with an energy larger than twice the band gap of the solar cell is down-converted into two photons, with an energy just above the band gap.

The photon conversion takes place in a material outside the solar cell, which is in good optical contact, but not in electrical contact with the solar cell. The photon converter must have the desired optical properties, but good transport properties are not required.

4.3.3. Intermediate band gap solar cell

In this concept an energy level between the valence and conduction bands in the absorber material provides additional transitions at lower energies. In addition to band–band transitions, electron-hole pairs can be generated in a two-step process, when an electron is first excited from the valence band to the intermediate level and then by a second photon from there to the conduction band. Such an intermediate level cell is equivalent to three cells in a tandem, where a series connection of the two cells represented by the transitions involving the intermediate level is connected in parallel to the third cell, which represents the band–band transitions.

4.3.4. Hot carrier cells

The thermalisation of photoexcited carriers with the atoms in the crystal lattice is one of the main loss mechanisms in conventional solar cells. The concept of a "hot carrier" cell seeks to avoid this loss. It can be done if the electrons and holes leave the absorber through semi-permeable membranes before they are thermalised by scattering with phonons. However, cooling of the energy carrier down to the temperature T_0 of the environment is an important step in the conversion process. As this cooling should not occur in the absorber, it must happen in the semi-permeable membranes. In order to avoid thermalisation losses there, only mono-energetic electrons (or holes) are allowed to pass into the membranes due, for example, to a narrow conduction band (or valence band).

4.3.5. Thermal approaches

Thermophotovoltaic (TPV) power generation is a process where the solar radiation is absorbed by an intermediate absorber/emitter combination, which is heated to a high temperature and emits near monochromatic radiation towards a

solar cell, either by virtue of its own selectivity or through a filter. In such an arrangement, all thermalisation losses in the solar cell are avoided and the unsuitable photons are not lost, since they are either not emitted or they are reflected back on to the intermediate absorber/emitter by the filter, which helps to maintain a high absorber temperature.

All these options require serious research consideration. The highest efficiencies for photovoltaic devices today are realised with mechanically stacked InGaP/GaAs/InGaAs 3-junction cells. Multi-junction cells based on III–V semiconductor materials are a realistic path to ultra high efficient solar cells. The most recent result was reported by SPECTROLAB at the end of July 2003. NREL has confirmed a 36.9% efficiency multi-junction concentrator device [13]. In combination with concentrator technology these cells are a near future option to play an important role in the future energy market.

5. Outlook

With all the different political developments, such as EU directives, national policies, etc., how are we now to reach the ambitious goals of the White Paper?

Fig. 14 shows the planned development to reach the White Paper targets and the actual status for 2002. The following methodology was used to determine the values for the generated electricity:

- Biomass: Here the data availability is very rare and the 2002 value is an extrapolation of the 1999 value reported by the PRETIR study [14].

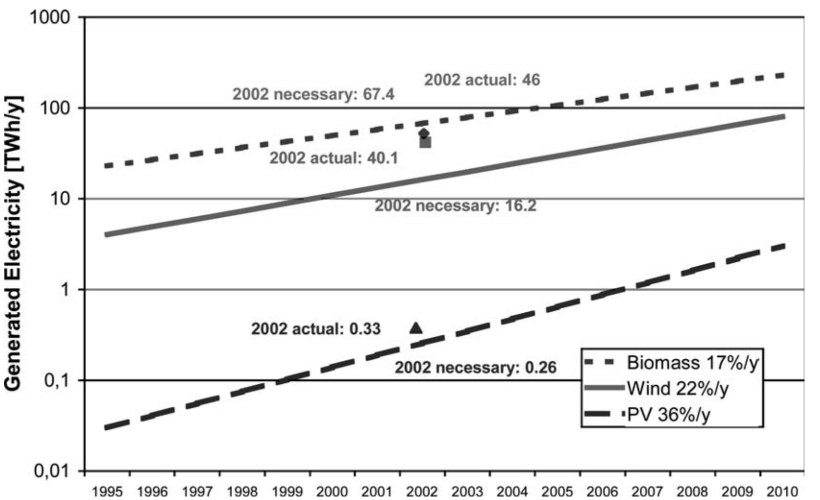


Fig. 14. Pathway to reach the White Paper targets and values for 2002. In order to reach the targets biomass must increase by 17%/year (10% until now), wind by 22% (39%) and PV by 36% (41%).

- Wind: The installed power of 2001 + 50% of the additional installations for 2002 are multiplied by 2000 h of operation. This reflects the fact that not all installed power in 1 year contributes to the actual electricity generation.
- PV: The installed power of 2001 + 50% of the additional installations for 2002 are multiplied by 1000 h of operation. For the whole of Europe this is a good average. However at the time being with approximately 70% of all the installations in Germany (Fig. 15) the electricity generation is slightly overestimated.

Wind and photovoltaics are well on track to reach the White Paper targets by 2010. For wind it can be even expected that it will already reach the target before 2010. However, the main concern is the electricity production from biomass as shown in Table 3. Here a major change in the implementation policies is needed in order to come even close to the set targets. As already pointed out in the Wind Section, the actual investment into a specific renewable energy does not depend primarily depend on the available resources, but on the policy measures take to promote it. The leading role of Germany in the field of wind and photovoltaic (Fig. 15) is due to the already mentioned renewable energy law, which is in 2003 under revision. A new version–continuing the support for renewable energies—is expected to enter into force at the beginning of 2004.

The analysis of the progress data showed that a great deal of fragmented data and interpretations are available, but they lack a consistent quality system for data verification and clearly defined criteria for their visualisation, comparison and interpretation. Discrepancies have to be identified and resolved, and better statistical methodologies elaborated, notably systematically including the New Accession States. A Scientific Reference System is needed to enhance the availability, quality and interpretation of renewable energy data. A one-stop-shop for policy and

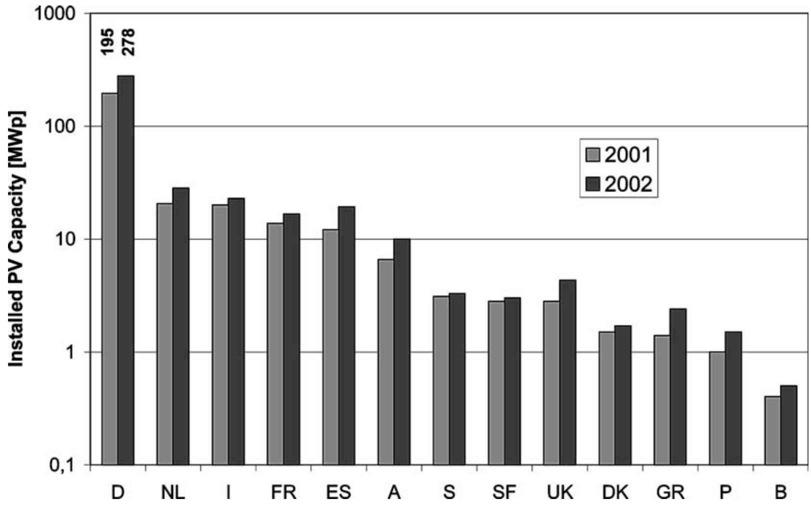


Fig. 15. 392 MWp installed PV capacity in Europe at the end of 2002 [15].

Table 3
Contribution and growth rates for different energy sources to reach the White Paper targets

Type of energy	Electricity produced (TWh/a)			Growth needed to reach White Paper targets	
	1995	2002	2010	1995 to 2010	2002 to 2010
Biomass	23	46	230	17% (real 10%)	22%
Wind	4	40.1	80	22% (real 39%)	9%
Photovoltaic	0,03	0,33	3	36% (real 41%)	32%

decision-makers is missing today, serving with unbiased, reliable inventory information on green energy technologies, potentials, investments, trends, markets, and comparisons with modelling results.

6. Conclusion

Electricity from biomass faces multiple challenges, which reflects the diversity of fuelling options and technologies. However, as it is very close to the conventional energy conversion chain, the introduction into the existing energy system could be managed with the necessary political support. Policy support is required to realise advanced conversion technologies and the development of appropriate expertise and market infrastructure in dedicated energy crop production. In a renewable energy scenario where different renewable energy sources are combined, biomass could play a leading role in buffering the energy needs during times when seasonal and time variable energy sources, like wind or PV have a low performance. If these measures are taken biomass could be brought on track for the White Paper targets.

Wind power is already a well-developed technology with a rapid growing worldwide market. The technological advances during the last decade have already made wind energy cost competitive with conventional energy sources in regions with good wind resources. Further cost reductions are predicted with economy of scale and new developments, even if the learning curve slows down over the next 10 to 20 years.

New market developments—offshore installations with larger turbines and building integrated installations with small turbines—as well as the expansion of wind into new world markets offer the chance that wind will indeed become a substantial part of tomorrow's sustainable power supply. To realise this policy support to develop these markets and realise the necessary cost reductions are needed.

Photovoltaics is right now on the brink of moving from a manufacture-type production to a fully fledged industry. This offers the possibility to make use of the economy of scale of large production units and lower the costs of PV systems considerably. PV still offers a large potential for cost reduction through market growth and innovation over the next decades. Already, PV offers cost competitive solutions not only for remote locations but also for peak load electricity, e.g. California. Building integration and grid connected PV is one of the main driving forces for market growth. To maintain this growth, stable economic and political

framing conditions are necessary to encourage private consumer and industry investments.

For all these renewable energy sources it holds true that they are all still diverse in terms of commercial and technological maturity. Some technical solutions are already close to economic competitiveness, while others are still at the stage of proving their effectiveness. Appropriate policies are needed to support research and development of promising options as well as market implementation and the fair access of renewable energies to the markets.

References

[1] EU Energy and Transport Figures, Statistical pocketbook 2002, European Commission, ISSN 1225-1095.
[2] Kyoto Protocol. http://unfccc.int/resource/docs/convkp/kpeng.pdf, 1997.
[3] Energy for the Future: Renewable Sources of Energy—White Paper for a Community Strategy and Action Plan; COM(97)599 final (26/11/1997); http://europa.eu.int/comm/energy/library/599fi_en.pdf.
[4] Green Paper, Towards a European strategy for the security of energy supply; COM 769 final (29/11/00); http://europa.eu.int/comm/energy_transport/doc-principal/pubfinal_en.pdf, 2000.
[5] Stipulated in Articles 2 and 6 of the Amsterdam Treaty on the European Union; http://europa.eu.int/eur-lex/en/treaties/dat/EU_consol.pdf, 1997
[6] Directive 2001/77/EC (27.09.2001); Official Journal of the European Communities L 283/33 (27.10.2001).
[7] Directive 2002/91.EC (16.12.2002); Official Journal of the European Communities L 1/65 (04.01.2003).
[8] Directive 2003/30/EC (08.05.2003); Official Journal of the European Communities L 123/42 (17.05.2003).
[9] Renewable Energy ... into the Mainstream; IEA working party publication; © November–October 2002.
[10] "Wind Force 12", Joint EWEA–Greenpeace report, May 2003; http://www.ewea.org/
[11] Spanish National Electricity System Act 40/1994.
[12] Paul Maycock, PV News, February 2003.
[13] Spectrolab press release 25 July 2003; http://www.spectrolab.com/com/news/news-detail.asp?id=152.
[14] PRETIR, Implementation of Renewable Energy in the European Union until 2010, ECOFYS June 2002.
[15] Photovoltaic Barometer, EurObservER; April 2003.